# High Temperature Superconducting State in Metallic Nanoclusters and Nano-Based Systems

**Yury Nikolaevich Ovchinnikov**

**Institution of Russian Academy of Sciences**
**L.D. Landau Institute for Theoretical Physics**
**Chernogolovka, Moscow region, pr.ac Semenova 1a**
**Russia**

Report Date: December 2013

Final Report from 01 October 2010 to 30 September 2013

**Air Force Research Laboratory**
**Air Force Office of Scientific Research**
**European Office of Aerospace Research and Development**
**Unit 4515, APO AE 09421-4515**

# REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

| 1. REPORT DATE *(DD-MM-YYYY)* | 2. REPORT TYPE | 3. DATES COVERED *(From – To)* |
|---|---|---|
| 16 December 2013 | Final Report | 1 October 2010 – 30 September 2013 |

**4. TITLE AND SUBTITLE**

**High Temperature Superconducting State in Metallic Nanoclusters and Nano-Based  Systems**

**5a. CONTRACT NUMBER**

**ISTC PPA 4084p**

**5b. GRANT NUMBER**

**ISTC 09-7006**

**5c. PROGRAM ELEMENT NUMBER**

61102F

**6. AUTHOR(S)**

**Yury Nikolaevich Ovchinnikov**

**5d. PROJECT NUMBER**

**5d. TASK NUMBER**

**5e. WORK UNIT NUMBER**

**7.  PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Institution of Russian Academy of Sciences
L.D. Landau Institute for Theoretical Physics
Chernogolovka, Moscow region, pr.ac Semenova 1a
Russia

**8. PERFORMING ORGANIZATION
REPORT NUMBER**

N/A

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

EOARD
Unit 4515
APO AE 09421-4515

**10. SPONSOR/MONITOR'S ACRONYM(S)**

AFRL/AFOSR/IOE (EOARD)

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

**AFRL-AFOSR-UK-TR-2014-0003**

**12. DISTRIBUTION/AVAILABILITY STATEMENT**

**Distribution A:  Approved for public release; distribution is unlimited.**

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**
The project is devoted to study of the new materials that are characterized with high value of the superconducting transition temperature (potentially up to room temperature). Nanoclusters with shell structure of the electron spectrum have been studied. Prospective objects are magic clusters, clusters with half filled upper zone, some flat molecules and two-dimensional quantum dots. We have studied the possibility of building such nano-based networks transferring a high value of dissipation-free current. The sours of energy dissipation are thermal and quantum fluctuations. The methods of modern quantum field theory were employed. Simultaneously, we searched the solutions of the nonlinear equations of the type of time-dependent Ginzburg-Landau equation and generalized Ginzburg-Landau functional. Main goal was to study the development of singularities of different kinds in such solutions at the finite time and investigation of new class of possible ground states in strong magnetic field, corresponding to Abrikosov lattices with several flux quantum in elementary cell. Results have been published or submitted to journals listed herein, with summaries included.

**15. SUBJECT TERMS**

EOARD, superconductivity, tunneling, nanocluster, critical current, quantum dot

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18, NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| **a. REPORT** | **b. ABSTRACT** | **c. THIS PAGE** | SAR | 7 | Lt Col Randall Pollak |
| UNCLAS | UNCLAS | UNCLAS | | | **19b. TELEPHONE NUMBER** *(Include area code)* +44 1895 616115, DSN 314-235-6115 |

**Standard  Form  298** (Rev.  8/98)
Prescribed by ANSI Std. Z39-18

# High Temperature Superconducting State in Metallic Nanoclusters and Nano-Based  Systems

ISTC Project No. 4084p (EOARD 097006)
1 Oct 2010  to 30 Sep 2013
Institution of Russian Academy of Sciences
L.D. Landau Institute for Theoretical Physics

**Project Manager:** Ovchinnikov Yury Nikolaevich, Doctor of Phys.-math. Sciences

**Director:** Lebedev Vladimir Valentinovich, Doctor Phys.-math. Sciences
* Corresponding  member of Russian Academy of Sciences

## Overall Summary

The project is devoted to study of the new materials that are characterized with high value of the superconducting transition temperature (potentially up to room temperature). Nanoclusters with shell structure of the electron spectrum have been studied. Prospective objects are magic clusters, clusters with half filled upper zone, some flat molecules and two-dimensional quantum dots. We have studied the possibility of building such nano-based networks transferring a high value of dissipation-free current. The sours of energy dissipation are thermal and quantum fluctuations. The methods of modern quantum field theory are employed. Simultaneously, we searched the solutions of the nonlinear equations of the type of time-dependent Ginzburg-Landau equation and generalized Ginzburg-Landau functional. Main goal was to study the development of singularities of different kinds in such solutions at the finite time and investigation of new class of possible ground states in strong magnetic field, corresponding to Abrikosov lattices with several flux quantum in elementary cell. Results have been published or submitted to journals listed herein, with summaries included.

## Summary of Relevant Findings

List of published papers and reports with abstracts:

*1. Yu.N.Ovchinnikov and V.Z.Kresin "Theoretical Investigation of Josephson Tunneling Between Nanoclusters" Phys.Rev.B 81, 214505 (1-6) (2010)*

Josephson tunneling between nanoclusters is analyzed. The discrete nature of the electron energy spectra, including their shell ordering, is explicitly taken into account. The treatment considers the two distinct cases of resonant and non-resonant tunneling. It is demonstrated that the current density greatly exceeds the value discussed in the conventional theory.

Nanoparticles are shown to be promising building blocks for nanomaterials based tunneling networks.

### 2. Yu.N.Ovchinnikov and V.Z.Kresin "Josephson effect between Nanoclusters in Resonant conditions" JETP 111, 82-86 (2010)

A general expression is derived for the Josephson current between nanoclusters. It is shown that in the resonance conditions between electron levels of clusters, the expression for the current, obtained in the tunnel Hamiltonian model, becomes invalid. In the case of degeneracy or close to degeneracy of energy levels in isolated clusters, the critical Josephson current may exceed the value, obtained in the model of tunnel Hamiltonian, in the large parameter, viz. the ratio of the order parameter "delta" to the distance between the resonance level and the levels closest to it.

### 3. Yu.N.Ovchinnikov and I.M.Sigal "Long Time Relaxation Processes in the Nonlinear Schrodinger Equation" JETP 112, 469-478 (2011)

The nonlinear Schrodinger equation, known in low-temperature physics as Gross-Pitaevskii equation, has a large family of excitations of different kinds. They include sound excitations, vortices and solitons. The dynamics of vortices strictly depends on the separation between them. For large distances some kind of adiabatic approximation can be used. We consider the case where an adiabatic approximation can be used (large separation between vortices) and the opposite case of a decay of the initial state, which is close to the double vortex solution. In the last problem no adiabatic parameter exist (interaction is strong). Nevertheless, a small numerical parameter arises in the problem of decay rate, connected with an existence of a large centrifugal potential, which leads to a small value of the increment. The properties of the nonlinear wave equation are briefly considered in Appendix A.

### 4. B.L.Jonsson, Yu.N.Ovchinnikov, I.M.Sigal.and F.S.T Ting "Dynamics of breakup of multiple vortices in Gross-Pitaevskii equation of super fluids" Journal of Mathematical Physics" 52,093505 (1-16) (2011)

In this paper we study the Gross-Pitaevskii equation of the theory of superfluidity, i.e. the nonlinear Schrodinger equation of the Ginzburg-Landau type. We investigate the dynamics of the breakup of the double vortex. More specifically, we prove instability of the double vortex, compute the complex eigenvalue responsible for this instability, and derive the dynamical equation of motion of (center of ) single vortices resulting from splitting of the double vortex. We expect that our analysis can be extended to vortices of higher degree and to magnetic and Chern-Simmons vortices.

### 5. Yu.N.Ovchinnikov, I.M.Sigal "On collapse of wave maps" Physica D240, 1311-1324 (2011)

We derive the universal collapse law for semilinear wave equation, that has non-normalized zero mode. To do this we introduce a nonlinear three parameters transformation from original variables to blowup ones. Our derivations are confirmed by numerical simulations.

### 6. Yu.N.Ovchinnikov, I.M.Sigal "Mean curvature flow of a hyperbolic" surface" JETP 113, N6, 1063-1070 (2011)

A four-parameter family of self-similar solutions is obtained to the mean curvature flow

equation for a surface. This family is shown to be stable with respect to a small deformation of a hyperbolic surface. At time instant t* a singular point is formed within a finite time interval, that is accompanied by a change in the topology of the surface. The solution is continued beyond the singular point. A relationship between the parameters describing the hyperbolic surface before and after the change in the surface topology is obtained. A particular case is analyzed when the unperturbed surface is a cylinder. A cylindrical surface is weakly unstable with respect to a perturbation in the form of a "wide neck". At the final stage of the shrinking of the neck when its transverse size becomes much less than the cylinder radius at large distances from the neck, the surface flow in a wide region in the neighborhood of the neck is described by a universal two –parameter family of self-similar solutions. These solutions are stable with respect to small perturbations of the surface.

### 7. Yu.N.Ovchinnikov, V.Z.Kresin "Artificial nets from superconducting nanoclusters" JETP 114, 1012-1017 (2012)

In the present paper we show, that large transport current can flow through superconducting nets composed of nano clusters. Although thermal and quantum fluctuations lead to a finite value of energy dissipation in one and two dimensional systems, this dissipation energy value may be very small for realistic parameters of the nano clusters and distances between them. The value of action for vortex tunneling at zero temperature can be made sufficiently large to make the dissipation energy negligible small. We estimate the value temperature "To", the transition from the thermal activation to quantum tunneling.

### 8. Yu.N.Ovchinnikov and Vladimir Kresin "Cluster-based superconducting tunneling network" Phys.Rev.B 85, 064518 (2012)

A two-dimensional tunneling network consisting of nanoclusters placed on a surface is studied. It is shown that such a network is capable of transferring a large supercurrent at high temperatures. For a realistic set of parameters the damping is quite small, and the smallness is due to strong renormalization of the capacitance of a cluster. The critical magnetic field also turns out to be large.

### 9. Yu.N.Ovchinnikov "Dynamics of an N-vortex State at Small Distances" JETP 116, N1, 173-179 (2013)

We investigate the dynamics of a state of N vortices, placed at the initial instant at small distances from some point, close to the "weight center" of vortices. The general solution of the time-dependent Ginzburg-Landau equation for N vortices in a large time interval is found. For N=2 the position of the "weight center" of two vortices is time independent. For N.≥3 the position of the "weight center" weakly depends on time and is located in the range of the order of $a^3$, where "a" is characteristic distance of a single vortex from the "weight center". For N=3 the time evolution of the N vortex state is fixed by the position of vortices at any time instant and by the values of two small parameters. For N≥4 a new parameters arises in the problem, connected with relative increases in the number of decay modes.

### 10. Vladimir Z.Kresin, Yu.N.Ovchinnikov "Superconducting State of Metallic Clusters: Potential for Room Temperature Superconductivity, Novel Nano-Based Tunneling Networks", J. Supercond. Nov. Magn.26, 745-748 (2013)

Metallic clusters contain delocalized electrons, and their states form energy shells similar to those in atoms or nuclei. Under special but perfectly realistic conditions, superconducting

pairing in such nanoclusters can become very strong, and they form a new family of high temperature superconductors. In principle, it is possible to raise Tc up to room temperature. The phenomenon is promising for the creation of high Tc superconducting tunneling networks, and hence macroscopic superconductivity. The synchronization of such networks is discussed.

***11. Yu.N.Ovchinnikov "Families of Solutions to the Generalized Ginzburg-Landau Equation and Structural Transitions between Them", JETP 117, N3, 480-486 (2013)***

Solutions to the generalized Ginzburg-Landau equations for superconductors are obtained for a Ginzburg-Landau parameter "κ "close to unity. The families of solutions with arbitrary number "n" of flux quanta in a unit cell are analyzed. It is shown that under certain conditions, a cascade of phase transitions between different structures in a magnetic field appears near Tc. Algebraic equations are derived for determining the boundaries of coexistence of different phases on the {T,H} plane.

***12. Yu.N.Ovchinnikov and Vladimir Z.Kresin" Networks of Josephson junctions and their synchronization", Phys.Rev.B 88, 214504(1-4) (2013)***

One can demonstrate that a 1D Josephson network containing junctions with different tunneling resistances can be synchronized at frequencies, which are multiples of 2eV, where V is the total dc voltage applied across the network. The appearance of such synchronization follows from the law of charge conservation and takes place if charge transfer is dominated by the Josephson channel. One can observe also a subharmonic structure. The result holds for cluster-based arrays as well as for the general case of a tunneling network.

***13 Yu.N.Ovchinnikov, Avik Halder, and Vitaly V.Kresin "Flat Thomas-Fermi artificial atoms: a fully consistent solution for confined quantum-dot electrons" to be published***

We consider the Thomas–Fermi description of two-dimensional "artificial atoms" confined by an axially symmetric potential $V(\rho)$. Such configuration arise in quantum dots and other systems effectively restricted to a 2D layer. The solution requires that a 2D density of state be properly combined with 3D electrostatics. This aspect, often passed over in the literature, leads to the appearance of singularities which require careful treatment. We present a full analytic solution for any $V(\rho)$. It has a universal form, scaling with $(\rho/R)^2$ and $S=R/(\pi a^*)$ (R-is dot radius, a*=effective Bohr radius). Specific equation for the electron density distribution and energy are given for the common case of harmonic confinement. A wide parameter range is found where perturbation theory with respect S or1/S is inapplicable. Within specific ranges, the results are in excellent agreement with numerical calculations and with the limiting case of a classical distribution.

List of relevant presentations at conferences and meetings with abstracts:

***1. Troizk, Institute of Physics of High Pressure RAS, June 2011, "Strong correlated electron systems and quantum critical phenomena" Yu.N.Ovchinnikov and V.Z.Kresin "Josephson effect between nanoclusters in resonance conditions"***

A general expression is derived for the Josephson current between nano clusters. In the case of degeneracy or close to degeneracy of energy levels of electrons in isolated clusters the critical current value may exceed the value of current, predicted in the model of tunnel Hamiltonian, in the large parameter, vis. the ratio of the order parameter Δ to the distance between the resonance level and closest to it.

*2. Chernogiolovka, L.D.Landau Institute for Theoretical Physics RAS , July 2011,"100-years, A.B.Migdal", Yu.N.Ovchinnikov, V.Z.Kresin "Superconductivity in nano clusters and nano based systems"*

The value of the superconducting transition temperature is investigated in nano clusters, having shell structure of electron spectrum similar to that in atoms or nuclei. The giant increasing of the Tc was found in special magic, near magic clusters and clusters with half filled upper shell (relative bulk samples). Nano clusters are shown to be promising building blocks for nono materials-based tunneling networks.

*3. Istanbul April 29 - May 07 (2012): ISCM "Superconductivity and Magnetism", V.Z.Kresin,Yu.N.Ovchinnikov "Superconducting State of Metallic clusters"*

Metallic clusters contain delocalized electrons, and their states form energy shells similar to those in atoms and nuclei. Under the special but perfectly realistic conditions superconducting pairing in such nano clusters can become very strong, and they form a new family of high temperature superconductors. In principle, it is possible to raise Tc up to room temperature. The phenomenon is promising for creation of high Tc superconducting tunneling networks, and hence macroscopic superconductivity. The synchronization of such networks is discussed.

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*5. Troizk, Institute of Physics  of High Pressure RAS,  June 2013 "Families of Solutions to the Generalized  Ginzburg-Landau Equation and Structural transitions between them", Yu.N.Ovchinnikov*

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